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DOCTOR OF PHILOSOPHY

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I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

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I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Jon F. Claerbout

I certify that I have read this dissertation and that in my opinion it is fully adequate, in scope and quality, as a dissertation for the degree of Doctor of Philosophy.

Gary Mavko

Approved for the University Committee on Graduate Studies:

Abstract

Current exploration geophysics practice still regards multiple reflections as noise, although multiples often contain considerable information about the earth's angle-dependent reflectivity that primary reflections do not. To exploit this information, multiples and primaries must be combined in a domain in which they are comparable, such as in the prestack image domain. However, unless the multiples and primaries have been pre-separated from the data, crosstalk leakage between multiple and primary images will significantly degrade any gains in the signal fidelity, geologic interpretability, and signal-to-noise ratio of the combined image. Moreover, by dividing the joint imaging process into individual separation and combination steps, each of which may produce biased results, it is difficult to ensure that the combined image honors the recorded data in any quantitative sense.

In this thesis, I present a global linear least-squares algorithm which simultaneously separates multiples from primaries and combines their information. The algorithm, denoted LSJIMP (Least-squares Joint Imaging of Multiples and Primaries), takes as input reflection seismic data with multiples, and outputs a set of images, each of which ideally contains energy only from the primaries or from one type of pegleg multiple. The novelty of the method lies in the three model regularization operators which both discriminate between crosstalk and signal and extend information between multiple and primary images. The LSJIMP method represents generalizations both of prestack algorithms which separate multiples and primaries and those which compensate for incomplete illumination. To better accomplish both goals, the method exploits another, hitherto ignored, source of redundancy in the data – that between primaries and multiples.

While many different types of multiple imaging operators are well-suited for use with the LSJIMP method, in this thesis I utilize an efficient prestack time imaging strategy for multiples which sacrifices accuracy in a complex earth for computational speed and convenience. I derive a variant of the normal moveout (NMO) equation for multiples, called HEMNO, which can image "split" pegleg multiples which arise from a moderately heterogeneous earth. I also derive a series of prestack amplitude compensation operators which when combined with HEMNO, transform pegleg multiples into events are directly comparable – kinematically and in terms of amplitudes – to the primary reflection.

I test my implementation of LSJIMP on two real datasets from the deepwater Gulf of Mexico. The first, a 2-D line in the Mississippi Canyon region, exhibits a variety of strong surface-related pegleg multiples – generated by shallow reflectors and by a tabular salt body – which strongly inhibit interpretation. The second dataset, consisting of portions of two sail lines extracted from a 3-D dataset acquired in the Green Canyon region, contains surface-related multiples which stacking mostly suppresses, but which nontheless inhibit prestack amplitude analysis. In both cases, LSJIMP excellently and non-destructively separates primaries from multiples, and moreover, reliably reconstructs missing traces and illumination gaps.

Preface

All of the figures in this thesis are marked with one of the three labels: [ER], [CR], and [NR]. These labels define to what degree the figure is reproducible from the data directory, source code and parameter files provided on the web version of this thesis [1].

ER denotes Easily Reproducible. The author claims that you can reproduce such a figure from the programs, parameters, and data included in the electronic document. We assume you have a UNIX workstation with Fortran, C, X-Window system, and the software on our CD-ROM at your disposal. Before the publication of the electronic document, someone other than the author tests the author's claim by destroying and rebuilding all ER figures.

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NR denotes Non-Reproducible. This class of figure is considered non-reproducible. Figures in this class are scans and artists' drawings. Output of interactive processing are labeled NR.

[1] http://sepwww.stanford.edu/public/docs/sep116

Acknowledgements

When I told my dad (also a geophysicist) of my acceptance to SEP, he warned me that the ride wouldn't be easy. Indeed! To outsiders, many aspects of the group may appear draconian: six SEP seminars per week, two SEP reports per year, computer maintenence/programming, 3-D real data requirement for the Ph.D. However, SEP alumni continually distinguish themselves as researchers, communicators, and independent problem-solvers; all would agree that Jon Claerbout's management formula explains why. I learned the equations of least-squares estimation in college, but Jon taught me how to make it *work*. Jon's a great theoretical mind, but long ago he realized that real data teaches important lessons to theoreticians. Synthetic data can be constructed to de-emphasize any inconvenient aspect of the earth's physics. Real data applies a crucial "reality filter" to research. Jon's insistence that SEP theses contain real data examples adds to student tenures, but it undoubtedly explains the group's long-term success.

Biondo Biondi has a tough job! Our field is fairly mature, corporate research efforts (and dollars) continue to wane, and we have no Arab oil embargo to reinforce the societal importance of finding new reserves (though oil now hovers above $40/barrel). Still, since taking a leadership role at SEP, Biondo has maintained the group's prestige and funding and fostered a diversity of research topics, while distinguishing himself as a world expert in 3-D seismic imaging. Biondo uses an impressive breadth of knowledge to push SEP into fruitful collaborative efforts in geostatistics, earthquake seismology, and environmental geophysics, to name a few. Much of the initial motivation for my thesis project arose from our joint work with Clement Kostov on the imaging of sub-basalt converted shear waves.

Every SEP student has contributed to my thesis, whether through a tough question in seminar or a comment at lunch. Still, I would like to especially thank Bob Clapp for his friendship, geophysical insights, and unprecedented efforts to improve SEP's computer resources. Antoine Guitton has been a good friend and collaborator in classes, research projects, and on many outdoor adventures. Paul Sava kindly provided the depth migration code used in Section **??**. Sergey Fomel's contributions to SEP's inversion and filtering libraries greatly enhanced my ability to generate results. I believe that some of the most fruitful and unexpected scientific discoveries occur when we communicate problems and insights that we would otherwise internalize at our computers. For me, much of that communication came on coffee breaks with many past and present SEP students: Sean Crawley, James Rickett, Antoine Guitton, Alejandro Valenciano, Gabriel Alvarez, Jesse Lomask, Brad Artman, and Bill Curry.

Alfonso Gonzalez suggested I apply to SEP and proved a thoughtful supervisor and mentor at Western Geophysical. Kurt Marfurt helped me considerably to prepare my Ph.D. proposal. Clement Kostov of WesternGeco planted the seed in my head to use "noise" like shear conversions and multiples as signal. Necati Gulunay of CGG expedited the release of the Green Canyon IV 3-D data. Diane Lau deserves special mention for her kindness and eminently competent work as SEP administrator. Professor John Scales of Colorado School of Mines provided encouragement at a critical juncture. I thank Professor Gary Mavko for serving on my reading committee and Professors Norm Sleep and Jef Caers for serving on my defense committee. Norm's insightful comments and careful reading of my thesis proved quite helpful.

I thank my parents for holding their tongues through my grad school rants. Advice from authority figures is cheap, and often destructive. Better to give young minds the resources to figure things out for themselves than to tell them exactly what to do. For thirty years, my parents have given me the love and support which fosters the self-confidence that in turn allows me to make my own decisions. It is odd that I delay my acknowledgement of my wife, Kimberly, to the end, because I sincerely believe that if not for Kim's love and support, this document would not exist! I can only imagine how the peculiar and stressful realities of SEP have percolated down from me down to her. I thank her for having the strength and patience to stick with me through this long, strange trip. Still, we have managed to grow so much as individuals and as a couple over the last five and half years. I look forward to the next fifty!

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